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Operational Use of Airborne Laser Scanning for Forestry Applications in Complex Mountainous Terrain

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Abstract

Today, airborne laser scanning (ALS) is the standard method for detailed topographic data acquisition, which can complement, or partly replace, other existing geo-data acquisition technologies, and open up new exciting areas of applications. With hydrology as the main driving force extensive ALS flight campaigns have been carried out since the disastrous floods 2002 in Austria and therefore, ALS data are available for large areas today. For forestry applications ALS is currently one of the most promising remote sensing techniques for quantitative retrieval of forest parameters. While ALS has reached an operational status for mapping of boreal forests, its large area application over mountainous environments is lacking behind. During the last years a few studies have been published, that successfully use small footprint ALS data for forestry applications in mountainous areas. However, it needs to be recognised that these studies were limited to small test sites, the reference data were measured during extensive field campaigns, and the used ALS data were acquired with homogenous system configurations. For operational applications of large areas, ALS data are normally acquired during several flight campaigns with varying system configurations. Thus, the algorithms used to derive forest attributes have to handle these different conditions.

This paper is a short summary of two studies (Hollaus et al., 2006a; Hollaus et al., 2006b), which have investigated the applicability of ALS data for a 128 km^2 test site in the western part of the Austrian Alps. On the basis of the derivation of canopy heights and of the estimation of stem volume it is discussed what can be reached with current ALS data and already available algorithms. The ALS data were acquired within the framework of an operational DTM mapping activity. The acquisition of the ALS data took place in two different seasons with varying ALS system configurations. For processing the ALS data only methods that are already implemented in commercially available software packages are used.

These two studies have shown that for large area applications the applied ALS pre-processing algorithm and the hierarchic robust filtering technique are adequate methods to derive high accurate topographic models for this complex environment. The validation of the ALS derived canopy height products (e.g. single tree heights and Lorey's mean heights) with operationally used forest inventory data and ground control points have shown good correlations using (1) three dimensional first-echo points and (2) a grid-based canopy height model. However, some inaccuracies of the canopy heights arose in areas covered by homogeneous meadows with high grass or scrubs due to the technical limitations of current ALS systems. For the estimation of stem volume a simple linear approach has been used to combine forest inventory and ALS data. The validation of the estimated stem volumes has shown that even for ALS data with varying properties (point densities, different acquisition times e.g. leaf-off and leaf-on) reliable results of high accuracies could be achieved. Concluding, it can be stated that ALS has now reached the maturity not only for topographic data acquisition but also for operational forestry applications within complex alpine environments.

KEY WORDS: Airborne laser scanning, forest inventory, mountainous forest, stem volume, canopy height

1. Introduction

In Austria, a significant portion of the alpine forest area is difficult to access and therefore field surveys are impossible or hampered, which increases labour efforts and costs. Schadauer et al. (1997) note that about a quarter of Austria's protection forest, an area of about 175000 ha, can not be accessed. Protection forests can be found in steep slopes and provide protection against natural hazards such as rockfall and snow avalanches. Therefore, remote sensing is often the only viable method for obtaining information about alpine forests. However, complex topography also poses significant challenges to remote sensing, affecting the complete processing chain from data acquisition to data analysis. This, in combination with the limited thematic content of remotely sensed data, has so far delayed a more widespread use of remote sensing techniques for large scale forestry applications in alpine environments.

Despite major advances in satellite technology, still today the most widely used remote sensing technique for operationally mapping alpine forests in Austria is airborne colour-infrared (CIR) photography. Especially for local forestry applications CIR images have the advantages that they are available at reasonable costs and that they are accepted within the forestry community as valuable data source. The interpretation of CIR images is commonly done manually and is therefore highly subjective. Consequently, there is on the one side the continued need to develop more automatic methods for classifying high resolution imagery and on the other side, remote sensing techniques which allow deriving quantitative forest attributes more directly are needed.

Today, one of the most promising techniques for the quantitative assessment of forest parameters is airborne laser scanning (ALS), also referred to as light detection and ranging (LiDAR). Airborne laser scanning is based on emitting short laser pulses towards the Earth's surface and on measuring round-trip times of return signals after diffusions and reflections on objects. As an active remote sensing technique ALS is not dependent on the sun as a source of illumination as it is the case for passive sensors operating in the optical domain. Consequently, the recorded signal is not influenced by shadows caused by clouds or neighbouring objects. When there are several objects within the travel path of the emitted laser pulse, multiple echoes are reflected. State-of-the-art ALS systems measure at least the round-trip time of the first- and last echo, novel sensors are capable of recording the full waveform of the backscattered signal (Wagner et al., 2006). In addition to recorded round-trip times, which are directly related to distances of the sensor to the objects, the direction of each laser beam is measured by the system. These polar coordinates of object points are transformed into a national ground survey coordinate system using the flight path positions measured with a differential Global Positioning System (dGPS) and an Inertial Measurement Unit (IMU). As a result, ALS systems provide a 3D point cloud, where over vegetated terrain some of the points are caused by reflections in the vegetation canopy and some by reflections at the ground surface. For the retrieval of digital terrain models (DTM) from this 3D data it is therefore necessary to firstly classify the points into terrain and non-terrain points. Then a DTM can be reconstructed from the terrain points by using an interpolation algorithm.

During the last decade rapid technical developments (sampling density, multiple echoes, positional accuracy, data storage, etc.), which have been mainly technology driven (Ackermann, 1999), have pushed up the initially measuring rates of 2 kHz to 100 kHz corresponding to approximately 20 points per square meter (p/m^2) from 1000 m flying height depending on the flying speed. Today, ALS is a well established technology for the highly automated generation of DTMs with high-quality (Ackermann, 1999; Kraus, 2003b; Wehr and Lohr, 1999). Additionally to these high technical advances, ALS has achieved high economic performance and has reached a status which is interesting also for other applications. As mentioned in Wehr and Lohr (1999), Kraus (2003a), and Maas and Vosselman (2004) ALS can complement, or partly replace, other existing geo-data acquisition techniques, and open up new exciting areas of application.

In general, ALS provides an irregular distributed 3D point cloud including points from ground surface, branches, leaves, needles, and man made objects. Therefore, ALS does not allow determining forest parameters directly. A common way to derive forest parameters (e.g. stem volume, basal area, tree height, crown closure, etc.) from ALS data is to build up relationships to field data using regression models. The field data are normally measured on a plot level and include the traditional forest parameters like tree height, diameter at breast height, and tree species. A comprehensive survey of using ALS in forestry is given by Lim et al. (2003), Hyyppä et al. (2004), and Næsset et al. (2004) who summarise the application of ALS in operational forest inventories in Norway, Sweden, and Finland respectively. Even though, ALS is in use for operational forest inventories in these countries, the use of ALS for forestry applications in alpine environments is reduced to small study areas. The reasons for that can be the complex topography, the relatively low point density achievable with former ALS systems, and finally the lack of appropriate algorithms. Furthermore, forests in alpine environments are more complex (e.g. high vertical and horizontal structure) than most of the Scandinavian ones.

2. Large area forestry applications of airborne laser scanning data for a mountainous environment

For forestry applications the most important quantity provided by ALS is the canopy height. The canopy height can be defined as the vertical extent of forested areas between the ground surface and the highest surface of the canopy, given in meters. Hollaus et al. (2006a) have analysed the accuracies of large-scale canopy heights derived from LiDAR data in a 128 km² large alpine test site. As shown in Fig. 1 the study area is situated in the western part of the Austrian Alps and covers approximately 30.7 km² forest amongst complex mountainous landscape, which is characterised by hilly to high alpine terrain. A single tree and an area based approach were used to investigate the canopy height accuracies.

Furthermore, Hollaus et al. (2006b) have used a physically-based linear model to estimate stem volume by combining forest inventory data and ALS data. The presented linear model only uses the canopy volumes as independent variables, which are calculated for sample plot subareas. The canopy volume represents the volume between the terrain surface and the top most surface of the tree tops and can be calculated from the ALS 3D points. The divisions of the plot areas depend on predefined, fixed canopy height ranges.

As reference data for both studies, field-measured forest inventory data were used, which are operationally used by the local forest administration Stand Montafon Forstfonds (Stand Montafon Forstfonds, May, 2006). Furthermore, 22000 ground control points to check the DTM were available. The used ALS data were acquired in the framework of a commercial DTM mapping project within two ALS flight campaigns with varying ALS system parameters. These two flight campaigns were carried out in an effort to map the complete area under snow free conditions, i.e. the lower lying parts were covered by 24 flight lines during the winter campaign (0.9 p/m²) under snow-free and leaf-off conditions, while the higher altitudes up to about 3000 m were covered by 52 flight lines during the summer campaign (2.7 p/m²) under snow-free and leaf-on conditions.

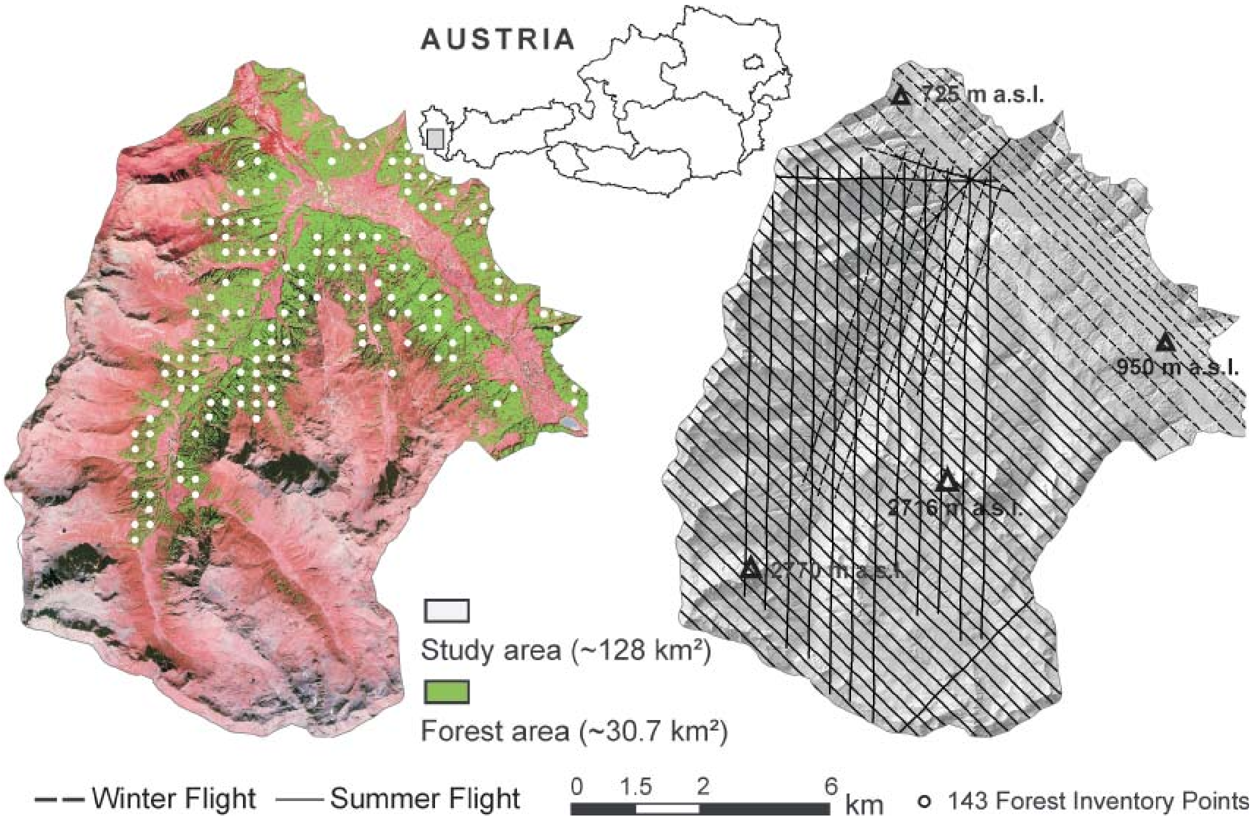

Figure 1: Location of the study area. The left image shows a mosaic of colour infrared orthophotos with highlighted forested areas. Furthermore, the positions of the 143 forest inventory sample plots are shown. The right image shows a shaded DTM overlain with the flight lines of the two ALS campaigns.

Due to the complex flight pattern, both in terms of the number of flight lines and variable flying heights above ground, the georeferencing of the ALS data were a demanding task. For the georeferencing of the data the method developed by Kager (2004) were applied. The georeferenced 3D point clouds were used to calculate the DTM, the digital surface model (DSM), the canopy height model (CHM), and canopy height points used for the stem volume estimation. The generation of the DTM were done with the widely-tested hierarchic robust filtering technique described in Kraus and Pfeifer (1998), Pfeifer et al. (1998) and Briese et al. (2002). Comprehensive information about the performance of this hierarchic robust filtering approach in comparison with several other available approaches can be found in Sithole and Vosselman (2004). While this was a computationally demanding task, the DSM was quickly generated by using a moving planes interpolation of the highest first-echo points within a pre-defined grid. The grid size for all calculated models was 1.0 m. Both algorithms are implemented in the commercial software package Scop++ (May, 2006).

One of the main objectives of these two studies was to use data and methods which already serve other operational applications rather than employing data and methods tuned for a particular task and for a small study area. Thus, it is ensured that the results obtained in these studies are of practical relevance. The aim of this presentation is to summarise the main results and to discuss the findings of these two large scale forestry applications. Finally, this presentation should contribute to an increased knowledge about the usability and potential of airborne laser scanner data for operational forestry applications in complex mountainous environments.

3. Results and experiences of canopy height mapping

The results from the investigation of Hollaus et al. (2006a) show that state-of-the-art ALS data, acquired for the main purpose of generating a DTM, are also an attractive data source for mapping canopy heights of alpine forests. Canopy heights were represented as interpolated canopy height model (CHM) and as point-based canopy heights. The CHM were calculated by subtracting the DTM from the DSM. Similar to the calculation of the CHM the calculation of the point-based canopy heights were based on the first- and last-echo ALS data but used the 3D first-echo points instead of the interpolated DSM. This means that for each first-echo points the terrain heights were subtracted. Since the DTM is the reference height for the computation of the canopy height products (e.g. single tree heights and the area-based Lorey's mean heights) errors in the DTM directly propagate into the achievable accuracies.

The investigations within this study show that the most critical part of canopy height assessment from ALS data is the correct estimation of the terrain height. For the validation of the DTM 22000 ground control points (GCPs) were used. The analyses have shown that for flat to gently sloping terrain (slope < 20%) the root mean square (RMS) errors are smaller than 0.2 m and increase rapidly with the steepness of the terrain (e.g. RMS errors rises up to more than 0.5 m for slopes greater than 60%). Especially in areas covered by dense coniferous forests the penetration rates of laser beams decrease to about 12 to 21% depending on the season (e.g. summer, winter). It can easily be envisaged that the representation of a rough forest ground is critical if the average ALS point density is in the range of 0.9 to 2.7 p/m^2. Furthermore, the study has shown that without an appropriate modelling of breaklines errors up to several meters can occur.

The direct validation of DSMs is difficult as no suitable reference data are available. A truly quantitative assessment of the ALS derived canopy heights were done with forest inventory data derived from regularly distributed sample plots, each representing a roughly circular area with a varying diameter (Bitterlich plots). The validations were done on a single-tree (e.g. single tree heights) and on an area-based (e.g. Lorey's mean heights) approach. To investigate the effects of the interpolated DSM, the canopy heights are extracted from both the first-echo point cloud and the grid-based CHM separately. As shown in Fig. 2, for the single tree based validation high accuracies could be achieved (e.g. tree heights extracted from 3D canopy height points: R^2 = 0.89, RMS = 2.4 m, mean residuals = -0.8 m), whereas the differences between the tree heights extracted from the DSM and the 3D canopy height points are low (e.g. tree heights extracted from the DSM: R^2 = 0.87, RMS = 2.6 m, mean residuals = 0.1 m). The mean residuals of single-tree heights derived from 3D canopy height points were surprising. From a physical point of view an underestimation would be expect mainly due to the low ALS point density, the small footprint size of approximately 0.3 m in diameter, and the conical tree crowns of spruces. Reasons for the overestimation of the tree heights are manifold and not yet fully understood. However, the following three reasons are assumed to be responsible. Due to the low penetration rate of laser beams in coniferous forests, the ground point density below tree crowns is very low. As the terrain point density fundamentally influences the DTM accuracy (Kraus et al., 2004) especially for rough forest terrain, surface smoothing effects and underestimation of the terrain heights appear. Secondly, an overestimation of the ALS derived tree heights can occur if trees lean toward the lower side of slopes as described in Hirata (2004). Thirdly, the timberline is situated at about 1950 m. Especially, for higher altitudes the probability that trees are interlocked to each other increases. Therefore, it is more difficult to extract single-tree heights. Additionally to these facts possible inaccuracies of the field measurements have to be considered. Considering all these uncertainties the derived correlations between the field-measured and the ALS derived tree heights are satisfactory.

The area-based validation of the ALS canopy heights is more complex as the forest inventory data do not reflect the canopy heights in a comparable manner to the ALS data. Due to the expected inaccuracies of the reference data (e.g. basal-area weighted mean tree heights, which is commonly called Lorey's mean heights), and the variable sample plot areas the calculated reference quantities are difficult to use. Nevertheless, the observed correlations (R^2 = 0.79, RMS error = 3.04 m, mean residuals = 0.53 m) between canopy height percentiles and Lorey's mean heights are good (Fig. 2) and confirm the consistency of the calculated canopy heights within the entire study area for different terrain conditions and ALS system configurations.

As the entire test site was covered by two ALS data sets with varying point densities their effects on the achievable accuracies of the extracted canopy heights (single-tree heights, Lorey's mean heights) were investigated. The results show that for the extracted single tree heights the RMS errors and the mean residuals increase and the R2s decrease with decreasing point densities. It can be recognised that the increase of the RMS errors and the mean residuals are less for the summer than for the winter data, which can be explained by the higher transparency for infrared laser pulses in winter than in summer (Hadley and Smith, 1986). Even though R2 decreases with decreasing point densities the achievable accuracies for winter (R^2 = 0.84, point density ~0.2 p/m^2) as well as for summer data (R^2 = 0.81, point density ~0.7 p/m^2) are high. For the estimation of the Lorey's mean heights the influence of different point densities on achievable accuracies is low. Especially, for R2 no significant influence could be observed. Finally, it can be stated that the influence of different point densities on the achievable accuracies is lower for Lorey's mean heights than for single tree heights. This can be explained by the averaging effects of the area based approach for extracting Lorey's mean heights. It could be shown that for the description of canopy heights for large areas, which are covered with ALS data with varying point densities, the Lorey's mean height is an appropriate forest parameter for operational canopy height mapping.

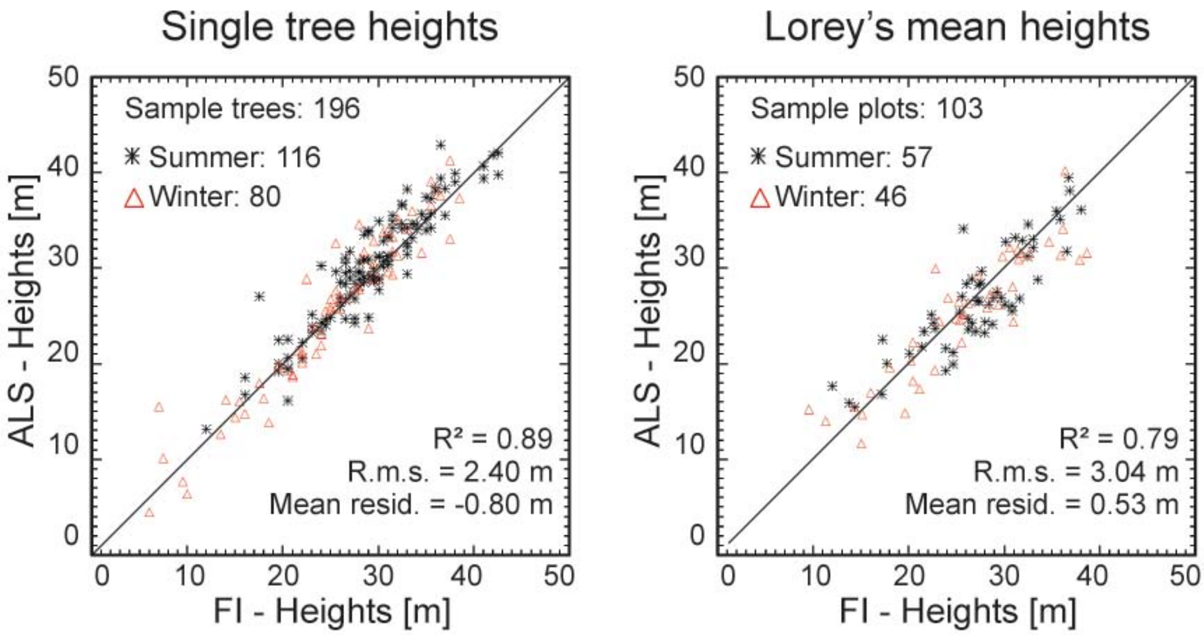

Figure 2: The left figure shows the comparison of single-tree heights derived from ALS data (3D canopy height points) and 196 measured single tree (spruce) heights. The right image shows the comparison of Lorey's mean heights derived from ALS data (3D canopy height points) and 103 forest inventory plots. © The figure is modified from Hollaus et al. (2006a).

4. Results and experiences of stem volume mapping

The estimation of stem volume for the entire test site is based on a linear model (Hollaus et al., 2006b) as shown in Fig. 3, which combines field-measured forest inventory and ALS data. The validation of the results using this linear approach show that for ALS data with varying properties (point densities, different acquisition times e.g. leaf-off and leaf-on) robust and reliable results of high accuracies

(R^2 = 0.87, RMS error = 90.4 m^3ha^{-1}, and the standard deviation of the residuals derived from a cross-validation is 90.4 m^3ha^{-1}) can be achieved (Fig. 3). Due to the simplicity of this linear model a physically explicit connection between the stem– and the canopy volume is available, which is represented by the β_i-coefficients. Therefore, the estimated β_i-coefficients represent the canopy- / stem volume ratios. Thus a plausibility check of the estimated β_i-coefficients can easily be done. The investigations have shown that the β_i-coefficients reach a maximum with canopy heights of 22 to 32 m, which indicates that the major part of stem volume can be found in areas covered with the mentioned canopy heights. Furthermore, the analyses have shown that the contributions of canopy volumes calculated for areas with canopy heights less than approximately 9 to 12 m are statistically not significant and can therefore be neglected for the final stem volume calculation.

Also for the estimation of stem volume the effects of different point densities on the achievable accuracies have been studied. For each ALS data set (winter, summer) the estimation of stem volume were done using several data sets, which were thinned out with different percentages. These investigations have shown that the effects of

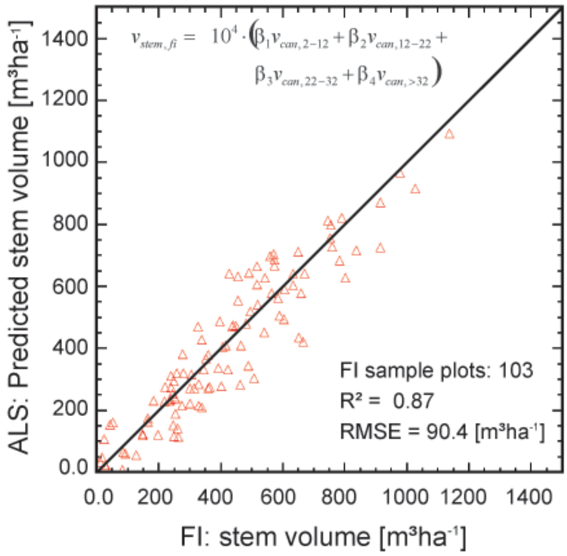

Figure 3: Scatter plots of stem volumes from ALS data versus forest inventory data. Furthermore, the used linear model to estimate the stem volume is shown. © The figure is modified from Hollaus et al. (2006b).

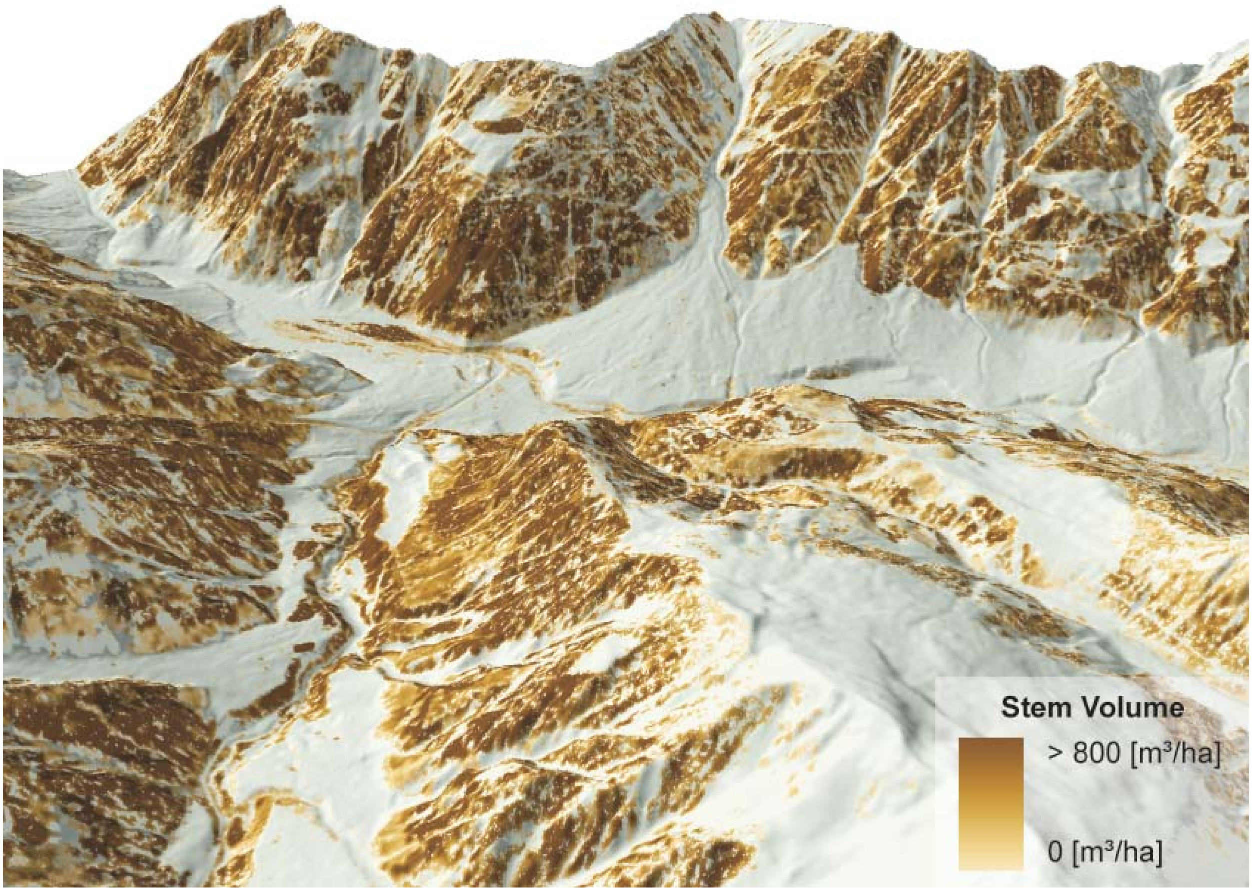

Figure 4: 3D-view of the estimated stem volume map for a subset of the test site. The line of sight is from south to north.

different point densities (0.2 to 2.7 p/m²) on the achieved stem volume accuracies (R^2 = 0.83 to 0.90) are statistically not significant. Also the comparison between leaf-off and leaf-on conditions has shown that R^2 and the RMS errors were marginal smaller for summer than for winter data. These minimal effects can be explained by the favourable circumstance that the region is dominated by coniferous tree species (spruce and fir). Consequently, the proposed model could successfully be used for the merged ALS data set as shown in Fig. 4.

5. Conclusions and outlook

Today, ALS is the most commonly used remote sensing technique to capture topographic data for the generation of high accurate DTMs and has widely replaced aerial photography for that purpose in many countries. Currently, extensive ALS campaigns are accomplished for DTM mapping activities in Austria. Thus, ALS data are available for large regions and provide an attractive data source for applied sciences and for several operational users. Especially, for forestry applications ALS is one of the most promising remote sensing techniques to estimate relevant parameters. However, until now the use of ALS for forestry applications in complex alpine environments was confirmed to small study areas. Therefore, the focus of this presentation was to summarise and discuss the results of two studies (Hollaus et al., 2006a; Hollaus et al., 2006b), which have investigated the applicability of ALS data for large area forestry applications for a complex alpine environment. On the basis of the derivation of canopy heights and of the estimation of stem volume it has been analysed and discussed what can be reached with current ALS data and already available algorithms.

In general these studies have shown that ALS data can successfully be used for large area estimation of forest parameters (e.g. single tree heights, Lorey's mean height, and stem volume) even for a complex mountainous terrain. However, it should not be expected that all ALS data are equally suited for the estimation of forest parameters and there are still a number of limitations that require further research and development work. One of most critical point is still the correct derivation of rough terrain surfaces below dense forests and for areas covered by low vegetation like bushes (e.g. dwarf pines). Due to technical limitations of current ALS systems the laser pulse duration is in the range of 5 ns to 10 ns, which leads to a range resolution of 0.75 m to 1.5 m. Thus, the correct identification of terrain points is of high importance to derive a DTM with a high accuracy. As mentioned in Wagner et al. (2006), novel full-waveform ALS systems provide in addition to multiple echoes, information about the echo width, the amplitude, and the cross-section of each target. First results have shown that this could improve the separation of ALS points into terrain and off-terrain points (also points from low vegetation) (Ducic et al., 2006) and therefore, the filtering process. To use this new information for forestry applications further research is needed.

For operational applications of ALS data quality control is of vital importance. Particularly over such difficult terrain, as can be found in the Austrian Alps, quality control has to be done very carefully. Within this presentation results of the validation of canopy heights using forest inventory data and ground control points were presented. In addition to the derived forest parameters the quality of the ALS data itself has to be checked. Therefore, it is planed to develop new methods and standards for quality control of ALS data. One of the main advantages of ALS techniques is the possible high degree of automatisation, covering the whole processing chain, from the acquisition to the analyses. In general, a high degree of automatisation for all processing steps leads to an increasing objectivity and therefore, to a repeatability of the results and to a reduction of the subjective influence of an individual operator. Furthermore, for the repeatability it is important to document all performed acquisition and processing steps, which can easily be reached with automated methods. Today, ALS data cover large areas and the amount of data is huge. Thus, the analyses can only be managed within an acceptable time frame with a highly automated processing chain. Finally, short processing times decrease the costs, which is essential for the operational usage of ALS data in various field of applications.

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